PATENT COOPERATION TREATY

From the INTERNATIONAL BUREAU

PCT

NOTIFICATION OF THE RECORDING OF A CHANGE

(PCT Rule 92bis.1 and Administrative Instructions, Section 422)

To:

REGAN, Heather
Harrison Goddard Foote
11C Compstall Road
Marple Bridge
Stockport SK6 5HH
ROYAUME-UNI

Date of mailing (day/month/year) 06 November 2000 (06.11.00)	
Applicant's or agent's file reference P60028WO	**IMPORTANT NOTIFICATION**
International application No. PCT/GB99/03428	**International filing date** (day/month/year) 22 October 1999 (22.10.99)

1. The following indications appeared on record concerning:

☐ the applicant ☐ the inventor ☒ the agent ☐ the common representative

Name and Address	State of Nationality	State of Residence
REGAN, Heather Harrison Goddard Foote 1 Stockport Road Marple Stockport SK6 6BD United Kingdom	Telephone No. 0161 427 7005	
	Facsimile No. 0161 427 7026	
	Teleprinter No.	

2. The International Bureau hereby notifies the applicant that the following change has been recorded concerning:

☐ the person ☐ the name ☒ the address ☐ the nationality ☐ the residence

Name and Address	State of Nationality	State of Residence
REGAN, Heather Harrison Goddard Foote 11C Compstall Road Marple Bridge Stockport SK6 5HH United Kingdom	Telephone No. 0161 427 7005	
	Facsimile No. 0161 427 7026	
	Teleprinter No.	

3. Further observations, if necessary:

4. A copy of this notification has been sent to:

☒ the receiving Office
☐ the International Searching Authority
☒ the International Preliminary Examining Authority
☐ the designated Offices concerned
☒ the elected Offices concerned
☐ other:

The International Bureau of WIPO **34, chemin des Colombettes** **1211 Geneva 20, Switzerland** Facsimile No.: (41-22) 740.14.35	Authorized officer Christine Carrié Telephone No.: (41-22) 338.83.38

PATENT COOPERATION TREATY

From the INTERNATIONAL BUREAU

PCT

NOTIFICATION OF ELECTION

(PCT Rule 61.2)

To:

Assistant Commissioner for Patents
United States Patent and Trademark Office
Box PCT
Washington, D.C.20231
ETATS-UNIS D'AMERIQUE

in its capacity as elected Office

Date of mailing (day/month/year) 23 June 2000 (23.06.00)	
International application No. PCT/GB99/03428	**Applicant's or agent's file reference** P60028WO
International filing date (day/month/year) 22 October 1999 (22.10.99)	**Priority date** (day/month/year) 23 October 1998 (23.10.98)
Applicant HERBERT, David, Charles, Wilfred et al	

1. The designated Office is hereby notified of its election made:

   [X] in the demand filed with the International Preliminary Examining Authority on:

   19 May 2000 (19.05.00)

   [ ] in a notice effecting later election filed with the International Bureau on:

2. The election [X] was [ ] was not

   made before the expiration of 19 months from the priority date or, where Rule 32 applies, within the time limit under Rule 32.2(b).

The International Bureau of WIPO **34, chemin des Colombettes** **1211 Geneva 20, Switzerland** Facsimile No.: (41-22) 740.14.35	Authorized officer Juan Cruz Telephone No.: (41-22) 338.83.38

REPLACED BY ART 34 AMDT PCT/GB99/03428

If an IMPATT device is mounted in a microwave cavity and a reverse bias voltage close to the breakdown voltage is applied, then the cavity can be tuned to allow the negative resistance of the diode to generate microwave oscillations with the diode voltage swinging above and below the breakdown voltage. When the rf voltage rises above zero (in its positive half cycle), an avalanche is initiated, a small number of holes and electrons arising from the reverse saturation current are greatly multiplied by the avalanche process. IMPATT diodes are normally designed so that the avalanche current peaks as the rf voltage approaches zero (towards the end of its positive half cycle). After passing through the avalanche region the electrons are swept into the low doped drift region and after a transit time delay the electrons are collected at the n^{++} contact region. Thus, the current resulting from the avalanche transits the drift region for the half period (negative half cycle) when the rf voltage is negative and this yields a negative resistance for rf current.

The IMPATT diode is one of the most powerful solid-state sources of microwave power. Continuous wave (CW) output powers as high as 10W at a few gigahertz and as high as 1W at 100GHz can be obtained from a single IMPATT diode device. However, IMPATT diodes are noisy and sensitive to operating conditions. The noise in an IMPATT diode arises mainly from the statistical nature of the generation rates of electron-hole pairs at and above the breakdown voltage. Noise can be reduced somewhat by operating an IMPATT diode well above the resonant frequency of the diode and keeping the current low. However, these conditions conflict with conditions favouring high power output and efficiency.

Partly, because of the high noise associated with IMPATT diodes, three terminal signal generators, such as transistors, are preferred at microwave frequencies, with subsequent up-conversion and low noise

amplification for higher frequencies. However, the high parasitics associated with three terminal structures indicates that two terminal devices, such as IMPATT diodes, would have a natural advantage at microwave and mm-wave frequencies if noise could be reduced.

The present invention seeks to overcome some of the problems discussed above by providing an IMPATT diode which operates with much reduced noise levels.

According to a first aspect of the present invention there is provided an impact ionisation avalanche transit time (IMPATT) diode device comprising an avalanche region and a drift region, wherein a narrow bandgap region, with a bandgap narrower than the bandgap in the avalanche region, is located adjacent to or within the avalanche region in order to generate within the narrow bandgap region a tunnel current which is injected into the avalanche region. By incorporating a narrow bandgap region adjacent to or within the avalanche region an injection tunnel current pulse can be generated in a predictable manner. This current pulse is injected into the main avalanche region where a low noise avalanche occurs.

Preferably, the narrow bandgap region is arranged to generate a tunnel current for injection into the avalanche region at the peak reverse bias voltage of an oscillating voltage applied across the terminals of the diode.

It is preferred that the narrow bandgap region is located at the edge of the avalanche region.

The doping profile of an IMPATT diode according to the present invention must be designed to achieve an electric field across the narrow bandgap region of sufficient magnitude to provide the desired

tunnel current amplitude at the peak reverse bias voltage. For strained semiconductor materials such as Silicon Germanium/Silicon, a plurality of alternating narrow and wide bandgap layers may have to be used to form the narrow bandgap region in order to alleviate strain. However, in unstrained materials such as Galium Arsenide/Aluminium Gallium Arsenide, one narrow bandgap layer may be used to form the narrow bandgap region.

Most of the noise associated with a conventional IMPATT diode occurs due to the statistical nature of the generation of electron-hole pairs during the part of the positive half cycle of the oscillating voltage when the voltage is above the threshold breakdown voltage. The diode structure according to the present invention increases the predictability of electron-hole pairs being generated at voltages above the breakdown voltage and so can enable a low noise narrow pulse of current to be generated close to the time at which the oscillating bias becomes negative.

The IMPATT diode according to the present invention may have a single drift form, for example having a lo-hi-lo doping profile or a Misawa p-i-n doping profile. Alternatively, the diode according to the present invention may be a double drift diode. In a preferred embodiment of the present invention particularly suitable for a single drift diode the narrow bandgap region is located between a heavily doped contact region and the avalanche region so as to maximise the proportion of the avalanche region which can be used to multiply the electrons generated in the narrow bandgap material. In a preferred embodiment of the present invention particularly suitable for a double drift diode the narrow bandgap region may be located within the avalanche region, preferably towards the centre of the avalanche region, so that both the n and p components of the tunnel current may undergo avalanche multiplication.

CLAIMS

1. An impact ionisation avalanche transit time (IMPATT) diode device comprising an avalanche region and a drift region, wherein a narrow bandgap region, with a bandgap narrower than the bandgap in the avalanche region, is located adjacent to or within the avalanche region in order to generate within the narrow bandgap region a tunnel current which is injected into the avalanche region.

2. An IMPATT diode according to claim 1 wherein the narrow bandgap region is arranged to generate a tunnel current for injection into the avalanche region at the peak reverse bias voltage applied to the diode.

3. An IMPATT diode according to claim 1 or claim 2 wherein the narrow bandgap region is located at the edge of the avalanche region.

4. An IMPATT diode according to any one of the preceding claims wherein the narrow bandgap region is located between a heavily doped contact region and the avalanche region.

5. An IMPATT diode according to any one of the preceding claims wherein the narrow bandgap region comprises one layer of narrow bandgap material.

6. An IMPATT diode according to any one of claims 1 to 4 wherein the narrow bandgap region comprises a plurality of layers of narrow bandgap material.

7. An IMPATT diode according to any one of the preceding claims wherein the diode has a lo-hi-lo doping profile.

8. An IMPATT diode according to claim 7 wherein the diode is a Misawa p-i-n diode.

9. An IMPATT diode according to any one of claims 1 to 6 wherein the diode is a double drift diode.

10. An IMPATT diode according to any one of the preceding claims wherein the diode is made of III-V semiconductor materials.

11. An IMPATT diode according to any one of claims 1 to 7 wherein the diode is made of group IV semiconductor materials.

12. An IMPATT diode according to claim 11 wherein the narrow bandgap region is made of at least one layer of Silicon Germanium and the avalanche region is made of Silicon.

13. An IMPATT diode according to claim 10 wherein the narrow bandgap region is made of at least one layer of Gallium Arsenide and the avalanche region is made of Aluminium Gallium Arsenide.

14. An IMPATT diode according to any one of the preceding claims wherein the length of the drift region or regions is between 2 and 6 times the length of the avalanche region.

15. An IMPATT diode according to claim 14 wherein the length of the drift region or regions is between 3.5 and 4.5 times the length of the avalanche region.

16. An IMPATT diode according to any one of the preceding claimed arranged such that at least part of the tunnel current can be generated by optical excitation.

17. An IMPATT diode substantially as hereinbefore described with reference to the accompanying Figures.

18. A method of operating an IMPATT diode according to any one of the preceding claims such that an oscillating voltage across the diode has a period of between 4 and 12 times the transit time of the avalanche region.

19. A method according to claim 18 wherein the oscillating voltage has a period of between 7.5 and 8.5 times the transit time of the avalanche region.

20. A method of operating an IMPATT diode according to any one of claims 1 to 17 including the step of optically exiting at least part of the tunnel current.

21. A method of operating an IMPATT diode substantially as hereinbefore described with reference to the accompanying Figures.

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REC'D 29 JAN 2001
WIPO PCT

PATENT COOPERATION TREATY

PCT

INTERNATIONAL PRELIMINARY EXAMINATION REPORT

(PCT Article 36 and Rule 70)

Applicant's or agent's file reference P60028WO	**FOR FURTHER ACTION**	See Notification of Transmittal of International Preliminary Examination Report (Form PCT/IPEA/416)
International application No. PCT/GB99/03428	International filing date *(day/month/year)* 22/10/1999	Priority date *(day/month/year)* 23/10/1998
International Patent Classification (IPC) or national classification and IPC H01L29/864		
Applicant THE SECRETARY OF STATE FOR DEFENCE et al.		

1. This international preliminary examination report has been prepared by this International Preliminary Examining Authority and is transmitted to the applicant according to Article 36.

2. This REPORT consists of a total of 6 sheets, including this cover sheet.

   ☒ This report is also accompanied by ANNEXES, i.e. sheets of the description, claims and/or drawings which have been amended and are the basis for this report and/or sheets containing rectifications made before this Authority (see Rule 70.16 and Section 607 of the Administrative Instructions under the PCT).

   These annexes consist of a total of 7 sheets.

3. This report contains indications relating to the following items:

   I ☒ Basis of the report
   II ☐ Priority
   III ☐ Non-establishment of opinion with regard to novelty, inventive step and industrial applicability
   IV ☐ Lack of unity of invention
   V ☒ Reasoned statement under Article 35(2) with regard to novelty, inventive step or industrial applicability; citations and explanations suporting such statement
   VI ☐ Certain documents cited
   VII ☒ Certain defects in the international application
   VIII ☒ Certain observations on the international application

Date of submission of the demand 19/05/2000	Date of completion of this report 25.01.2001
Name and mailing address of the international preliminary examining authority: European Patent Office D-80298 Munich Tel. +49 89 2399 - 0 Tx: 523656 epmu d Fax: +49 89 2399 - 4465	Authorized officer Madenach, A Telephone No. +49 89 2399 2832

I. Basis of th r p rt

1. This report has been drawn on the basis of *(substitute sheets which have been furnished to the receiving Office in response to an invitation under Article 14 are referred to in this report as "originally filed" and are not annexed to the report since they do not contain amendments (Rules 70.16 and 70.17).)*:
Description, pages:

1,5-16	as originally filed			
2-4,4a	as received on	05/10/2000	with letter of	05/10/2000

Claims, No.:

1-19	as received on	05/10/2000	with letter of	05/10/2000

Drawings, sheets:

1-5	as originally filed

2. With regard to the **language**, all the elements marked above were available or furnished to this Authority in the language in which the international application was filed, unless otherwise indicated under this item.

   These elements were available or furnished to this Authority in the following language: , which is:

   ☐ the language of a translation furnished for the purposes of the international search (under Rule 23.1(b)).
   ☐ the language of publication of the international application (under Rule 48.3(b)).
   ☐ the language of a translation furnished for the purposes of international preliminary examination (under Rule 55.2 and/or 55.3).

3. With regard to any **nucleotide and/or amino acid sequence** disclosed in the international application, the international preliminary examination was carried out on the basis of the sequence listing:

   ☐ contained in the international application in written form.
   ☐ filed together with the international application in computer readable form.
   ☐ furnished subsequently to this Authority in written form.
   ☐ furnished subsequently to this Authority in computer readable form.
   ☐ The statement that the subsequently furnished written sequence listing does not go beyond the disclosure in the international application as filed has been furnished.
   ☐ The statement that the information recorded in computer readable form is identical to the written sequence listing has been furnished.

4. The amendments have resulted in the cancellation of:

☐ the description, pages:
☐ the claims, Nos.:
☐ the drawings, sheets:

5. ☐ This report has been established as if (some of) the amendments had not been made, since they have been considered to go beyond the disclosure as filed (Rule 70.2(c)):

   (Any replacement sheet containing such amendments must be referred to under item 1 and annexed to this report.)

6. Additional observations, if necessary:

V. Reasoned statement under Article 35(2) with regard to novelty, inventive step or industrial applicability; citations and explanations supporting such statement

1. Statement

Novelty (N)	Yes:	Claims	
	No:	Claims	1-13, 16, 19
Inventive step (IS)	Yes:	Claims	
	No:	Claims	14, 15, 17, 18
Industrial applicability (IA)	Yes:	Claims	1-19
	No:	Claims	

2. Citations and explanations
   see separate sheet

VII. Certain defects in the international application

The following defects in the form or contents of the international application have been noted:
see separate sheet

VIII. Certain observations on the international application

The following observations on the clarity of the claims, description, and drawings or on the question whether the claims are fully supported by the description, are made:
see separate sheet

The following comments relate to items II-VIII of the cover sheet where they have been crossed:

1. The application does not meet the requirements of Article 6 PCT, because claim **1** is not clear.

1.1 The wording of claim 1 is not clear as the meaning of "main" is unspecific. In particular, it is not clear whether the "main" avalanche region is the region which is bigger in size or has more electron hole pairs generated in absolute number or in number relative to the volume or anything else. It is to be pointed out that it follows from the description (see eg. Fig. 3) that the narrow bandgap region is also a region of avalanche multiplication. There is no net distinction between the narrow bandgap region and a "main" avalanche region possible in as far as the avalanche effect is concerned.

2. The amendments filed with the letter dated **5.10.00** introduce subject-matter which extends beyond the content of the application as filed, contrary to Article 34(2)(b) PCT.

   The amendments concerned are the following:

   The separation of the avalanche region into a "main" avalanche region and into an additional narrow bandgap region does not seem to be justified by the original disclosure.

3. Reference is made to the following documents:

   D1: EP-A-0 262 346 (LICENTIA GMBH) 6 April 1988 (1988-04-06)
   D2: GB-A-2 002 579 (THOMSON CSF) 21 February 1979 (1979-02-21)
   D3: US-A-5 466 965 (MENG CHARLES C ET AL) 14 November 1995 (1995-11-14)
   D4: EP-A-0 757 392 (HITACHI EUROP LTD) 5 February 1997 (1997-02-05)
   D5: MISHRA J K ET AL: 'DESIGN OPTIMIZATION OF A SINGLE-SIDED SI/SIGE HETEROSTRUCTURE MIXEDTUNNELLING AVALANCHE TRANSIT TIME DOUBLE DRIFT REGION' SEMICONDUCTOR SCIENCE AND

TECHNOLOGY,GB,INSTITUTE OF PHYSICS. LONDON, vol. 12, no. 12, page 1635-1640 XP000724838 ISSN: 0268-1242
D6: MISHRA J K ET AL: 'AN EXTREMELY LOW NOISE HETEROJUNCTION IMPATT' IEEE TRANSACTIONS ON ELECTRON DEVICES,US,IEEE INC. NEW YORK, vol. 44, no. 12, page 2143-2148 XP000724127 ISSN: 0018- 9383
D7: KEARNEY M J: 'HETEROJUNCTION IMPACT AVALANCHE TRANSITTIME DIODES GROWN BY MOLECULAR BEAM EPITAXY' SEMICONDUCTOR SCIENCE AND TECHNOLOGY,GB,INSTITUTE OF PHYSICS. LONDON, vol. 8, no. 4, page 560-567 XP000368239 ISSN: 0268-1242

4. In view of the above unclarity, the present application does not meet the requirements of Article 33(2) PCT, because the subject-matter of claims **1-13, 16, 19** is not new.

3.1 Heterojunction IMPATT-diodes according to claim 1 seem to be known from any of D1-D7.

3.2 The further features of claims 2-13, 16 and 19 seem also to be known from these documents, document D1 disclosing the features of claims 2-6, 8, 11, 12, 16; D2 those of claims 2-6, 10; D3 those of claims 2-7, 10, 13, 16, 19; D4 those of claims 2-5, 7, 8, 10; D5 those of claims 2-6, 9, 11, 12, 16; D6 those of claims 2, 10; and D7 those of claims 7, 13.

4. The present application does not meet the requirements of Article 33(3) PCT, because the subject-matter of claims **14, 15, 17, 19** does not comprise an inventive step.

The particular length relations as claimed in claims 14 and 15 and the ensuing oscillating voltages as claimed in claims 17, 18 are routinely optimised by the skilled person. The resulting values will of course depend on the materials involved and might for particular material combinations overlap with the claimed values. The optimisation of these values in particular in view of the new properties of the IMPATT diode (see p. 8, l. 20-28 of the application) is obvious for the skilled person according to the discussion relating to Fig. 4 of D5.

5. Contrary to the requirements of Rule 5.1(a)(ii) PCT, the relevant background art disclosed in the documents D5-D7 is not mentioned in the description, nor are these documents identified therein.

   To meet the requirements of Rule 6.3 b) PCT the independent claim should be properly cast in the two part form, with those features which in combination are part of the prior art (see document D1 or any other suitable document of D2-D7) being placed in the preamble.

PATENT COOPERATION TREATY

PCT

INTERNATIONAL SEARCH REPORT

(PCT Article 18 and Rules 43 and 44)

Applicant's or agent's file reference P60028WO	**FOR FURTHER ACTION** see Notification of Transmittal of International Search Report (Form PCT/ISA/220) as well as, where applicable, item 5 below.	
International application No. PCT/GB 99/ 03428	International filing date *(day/month/year)* 22/10/1999	(Earliest) Priority Date *(day/month/year)* 23/10/1998
Applicant THE SECRETARY OF STATE FOR DEFENCE et al.		

This International Search Report has been prepared by this International Searching Authority and is transmitted to the applicant according to Article 18. A copy is being transmitted to the International Bureau.

This International Search Report consists of a total of 3 sheets.

[X] It is also accompanied by a copy of each prior art document cited in this report.

1. **Basis of the report**
   a. With regard to the **language**, the international search was carried out on the basis of the international application in the language in which it was filed, unless otherwise indicated under this item.
      - [ ] the international search was carried out on the basis of a translation of the international application furnished to this Authority (Rule 23.1(b)).

   b. With regard to any **nucleotide and/or amino acid sequence** disclosed in the international application, the international search was carried out on the basis of the sequence listing :
      - [ ] contained in the international application in written form.
      - [ ] filed together with the international application in computer readable form.
      - [ ] furnished subsequently to this Authority in written form.
      - [ ] furnished subsequently to this Authority in computer readble form.
      - [ ] the statement that the subsequently furnished written sequence listing does not go beyond the disclosure in the international application as filed has been furnished.
      - [ ] the statement that the information recorded in computer readable form is identical to the written sequence listing has been furnished

2. [ ] **Certain claims were found unsearchable** (See Box I).
3. [ ] **Unity of invention is lacking** (see Box II).

4. With regard to the **title**,
   - [X] the text is approved as submitted by the applicant.
   - [ ] the text has been established by this Authority to read as follows:

5. With regard to the **abstract**,
   - [X] the text is approved as submitted by the applicant.
   - [ ] the text has been established, according to Rule 38.2(b), by this Authority as it appears in Box III. The applicant may, within one month from the date of mailing of thi international search report, submit comments to this Authority.

6. The figure of th drawings to be published with the abstract is Figure No. 1
   - [X] as suggested by the applicant.
   - [ ] because the applicant failed to suggest a figure.
   - [ ] because this figure better characterizes the invention.
   - [ ] None of the figures.

Form PCT/ISA/210 (first sheet) (July 1998)

A. CLASSIFICATION OF SUBJECT MATTER
IPC 7 H01L29/864

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 7 H01L

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	EP 0 262 346 A (LICENTIA GMBH) 6 April 1988 (1988-04-06)	1-6,8, 11,12, 16,17,21
A	page 3, column 4, line 22 - line 23; figures 1,2	14,15, 18,19
X	MISHRA J K ET AL: "DESIGN OPTIMIZATION OF A SINGLE-SIDED SI/SIGE HETEROSTRUCTURE MIXEDTUNNELLING AVALANCHE TRANSIT TIME DOUBLE DRIFT REGION" SEMICONDUCTOR SCIENCE AND TECHNOLOGY,GB,INSTITUTE OF PHYSICS. LONDON, vol. 12, no. 12, page 1635-1640 XP000724838 ISSN: 0268-1242 page 1636, column 2, paragraph 3	1-6,9, 11,12, 16,17,21

-/--

[X] Further documents are listed in the continuation of box C.

[X] Patent family members are listed in annex.

° Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance
"E" earlier document but published on or after the international filing date
"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)
"O" document referring to an oral disclosure, use, exhibition or other means
"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.
"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
13 January 2000	24/01/2000

Name and mailing address of the ISA	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax: (+31-70) 340-3016	Juhl, A

1

C.(Continuation) DOCUMENTS CON… …ED TO BE RELEVANT

Category °	Citation of document, with indication,where appropriate, of the relevant passages	Relevant to claim No.
X	GB 2 002 579 A (THOMSON CSF) 21 February 1979 (1979-02-21) figure 2	1-6,10, 17,21
X	US 5 466 965 A (MENG CHARLES C ET AL) 14 November 1995 (1995-11-14)	1-7,10, 13,16, 17,20,21
A	figure 1	14,15
X	EP 0 757 392 A (HITACHI EUROP LTD) 5 February 1997 (1997-02-05) page 6, line 19; figures 35,36 page 19, line 2	1-5,7,8, 10
X	MISHRA J K ET AL: "AN EXTREMELY LOW NOISE HETEROJUNCTION IMPATT" IEEE TRANSACTIONS ON ELECTRON DEVICES,US,IEEE INC. NEW YORK, vol. 44, no. 12, page 2143-2148 XP000724127 ISSN: 0018-9383 figure 1	1,2,10
X	KEARNEY M J: "HETEROJUNCTION IMPACT AVALANCHE TRANSITTIME DIODES GROWN BY MOLECULAR BEAM EPITAXY" SEMICONDUCTOR SCIENCE AND TECHNOLOGY,GB,INSTITUTE OF PHYSICS. LONDON, vol. 8, no. 4, page 560-567 XP000368239 ISSN: 0268-1242 figure 1	1,7,13

1

INTERNATIONAL SEARCH REPORT

Information on patent family members

International Application No
PCT/GB 99/03428

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
EP 0262346 A	06-04-1988	DE 3725214 A	31-03-1988
		DE 3785126 A	06-05-1993
		US 4857972 A	15-08-1989
GB 2002579 A	21-02-1979	FR 2399740 A	02-03-1979
		CA 1104265 A	30-06-1981
		DE 2833543 A	15-02-1979
		JP 54052481 A	25-04-1979
		US 4186407 A	29-01-1980
US 5466965 A	14-11-1995	NONE	
EP 0757392 A	05-02-1997	JP 9121061 A	06-05-1997

INTERNATIONAL SEARCH REPORT

International Application No
PCT/GB 99/03428

A. CLASSIFICATION OF SUBJECT MATTER
IPC 7 H01L29/864

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 7 H01L

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	EP 0 262 346 A (LICENTIA GMBH) 6 April 1988 (1988-04-06)	1-6,8, 11,12, 16,17,21
A	page 3, column 4, line 22 - line 23; figures 1,2 ---	14,15, 18,19
X	MISHRA J K ET AL: "DESIGN OPTIMIZATION OF A SINGLE-SIDED SI/SIGE HETEROSTRUCTURE MIXEDTUNNELLING AVALANCHE TRANSIT TIME DOUBLE DRIFT REGION" SEMICONDUCTOR SCIENCE AND TECHNOLOGY,GB,INSTITUTE OF PHYSICS. LONDON, vol. 12, no. 12, page 1635-1640 XP000724838 ISSN: 0268-1242 page 1636, column 2, paragraph 3 ---	1-6,9, 11,12, 16,17,21

-/--

[X] Further documents are listed in the continuation of box C.

[X] Patent family members are listed in annex.

° Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier document but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
13 January 2000	24/01/2000

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INTERNATIONAL SEARCH REPORT

Int[redacted]ional Application No
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C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	GB 2 002 579 A (THOMSON CSF) 21 February 1979 (1979-02-21) figure 2	1-6,10, 17,21
X	US 5 466 965 A (MENG CHARLES C ET AL) 14 November 1995 (1995-11-14)	1-7,10, 13,16, 17,20,21
A	figure 1	14,15
X	EP 0 757 392 A (HITACHI EUROP LTD) 5 February 1997 (1997-02-05) page 6, line 19; figures 35,36 page 19, line 2	1-5,7,8, 10
X	MISHRA J K ET AL: "AN EXTREMELY LOW NOISE HETEROJUNCTION IMPATT" IEEE TRANSACTIONS ON ELECTRON DEVICES,US,IEEE INC. NEW YORK, vol. 44, no. 12, page 2143-2148 XP000724127 ISSN: 0018-9383 figure 1	1,2,10
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INTERNATIONAL SEARCH REPORT

Information on patent family members

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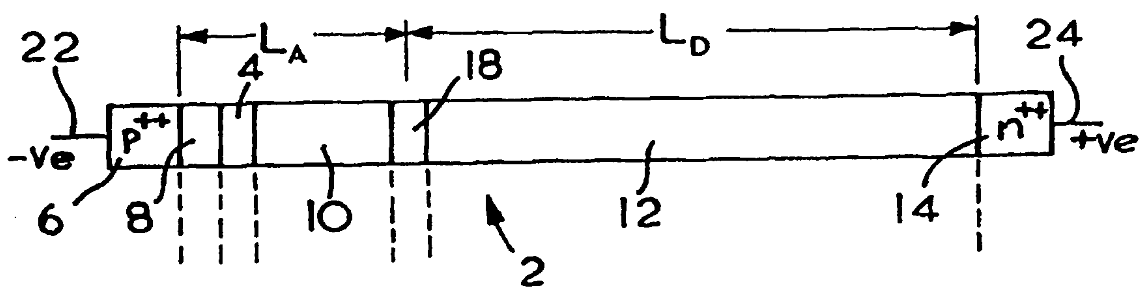

(57) Abstract

The present invention relates to an impact ionisation avalanche transit time (IMPATT) diode device comprising an avalanche region and a drift region, wherein at least one narrow bandgap region, with a bandgap narrower than the bandgap in the avalanche region, is located adjacent to or within the avalanche region in order to generate within the narrow bandgap region a tunnel current which is injected into the avalanche region. This improves the predictability with which a current can be injected into the avalanche region and enables a relatively narrow pulse of current to be injected into the avalanche region in order to enable a relatively noise free avalanche multiplication. The narrow bandgap region may be located between a heavily doped contact region and the avalanche region and is preferably arranged to generate a tunnel current at the peak reverse bias applied to the diode.

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Improvements in IMPATT Diodes

The present invention relates to semiconductor avalanche diodes, and in particular to IMPATT (impact ionisation avalanche transit time) diodes.

IMPATT diodes employ the impact-ionisation and transit time properties of semiconductor structures to produce negative resistance at microwave frequencies. An IMPATT diode consists of heavily doped n^{++} and p^{++} contact regions separated by a depleted region with a doping profile designed to produce an avalanche region and a drift region. The doping profile is designed to produce an avalanche region with a high electric field, sufficient to generate high multiplication levels by impact ionisation. The doping profile is designed to produce a drift region with an electric field sufficiently high to achieve carrier velocity saturation but sufficiently low to avoid impact ionisation.

A common example of an IMPATT diode has a lo-hi-lo doping profile in which the p^{++} contact region is followed by a n-type doped region, in which a first layer (adjacent to the p^{++} contact region) has a low doping concentration (n), a second layer has a high doping concentration (n^{+}) and a third layer has a low doping concentration (n). The first layer is the avalanche region and sustains a high electric field, the second layer is a doping spike to switch the electric field from a high value in the first layer to a lower value in the third layer, which is the drift region. The avalanche region of the diode will break down when the applied reverse bias voltage exceeds a threshold value.

Close to the breakdown voltage a rapid increase in current is caused by avalanche multiplication of holes and electrons in the avalanche region.

If an IMPATT device is mounted in a microwave cavity and a reverse bias voltage close to the breakdown voltage is applied, then the cavity can be tuned to allow the negative resistance of the diode to generate microwave oscillations with the diode voltage swinging above and below the breakdown voltage. When the rf voltage rises above zero (in its positive half cycle), an avalanche is initiated, a small number of holes and electrons arising from the reverse saturation current are greatly multiplied by the avalanche process. IMPATT diodes are normally designed so that the avalanche current peaks as the rf voltage approaches zero (towards the end of its positive half cycle). After passing through the avalanche region the electrons are swept into the low doped drift region and after a transit time delay the electrons are collected at the n^{++} contact region. Thus, the current resulting from the avalanche transits the drift region for the half period (negative half cycle) when the rf voltage is negative and this yields a negative resistance for rf current.

The IMPATT diode is one of the most powerful solid-state sources of microwave power. Continuous wave (CW) output powers as high as 10W at a few gigahertz and as high as 1W at 100GHz can be obtained from a single IMPATT diode device. However, IMPATT diodes are noisy and sensitive to operating conditions. The noise in an IMPATT diode arises mainly from the statistical nature of the generation rates of electron-hole pairs at and above the breakdown voltage. Noise can be reduced somewhat by operating an IMPATT diode well above the resonant frequency of the diode and keeping the current low. However, these conditions conflict with conditions favouring high power output and efficiency.

Partly, because of the high noise associated with IMPATT diodes, three terminal signal generators, such as transistors, are preferred at microwave frequencies, with subsequent up-conversion and low noise

amplification for higher frequencies. However, the high parasitics associated with three terminal structures indicates that two terminal devices, such as IMPATT diodes, would have a natural advantage at microwave and mm-wave frequencies if noise could be reduced.

The present invention seeks to overcome some of the problems discussed above by providing an IMPATT diode which operates with much reduced noise levels.

According to a first aspect of the present invention there is provided an impact ionisation avalanche transit time (IMPATT) diode device comprising an avalanche region and a drift region, wherein a narrow bandgap region, with a bandgap narrower than the bandgap in the avalanche region, is located adjacent to or within the avalanche region in order to generate within the narrow bandgap region a tunnel current which is injected into the avalanche region. By incorporating a narrow bandgap region adjacent to or within the avalanche region an injection tunnel current pulse can be generated in a predictable manner. This current pulse is injected into the main avalanche region where a low noise avalanche occurs.

Preferably, the narrow bandgap region is arranged to generate a tunnel current for injection into the avalanche region at the peak reverse bias voltage of an oscillating voltage applied across the terminals of the diode.

It is preferred that the narrow bandgap region is located at the edge of the avalanche region.

The doping profile of an IMPATT diode according to the present invention must be designed to achieve an electric field across the narrow bandgap region of sufficient magnitude to provide the desired

tunnel current amplitude at the peak reverse bias voltage. For strained semiconductor materials such as Silicon Germanium/Silicon, a plurality of alternating narrow and wide bandgap layers may have to be used to form the narrow bandgap region in order to alleviate strain. However, in unstrained materials such as Galium Arsenide/Aluminium Gallium Arsenide, one narrow bandgap layer may be used to form the narrow bandgap region.

Most of the noise associated with a conventional IMPATT diode occurs due to the statistical nature of the generation of electron-hole pairs during the part of the positive half cycle of the oscillating voltage when the voltage is above the threshold breakdown voltage. The diode structure according to the present invention increases the predictability of electron-hole pairs being generated at voltages above the breakdown voltage and so can enable a low noise narrow pulse of current to be generated close to the time at which the oscillating bias becomes negative.

The IMPATT diode according to the present invention may have a single drift form, for example having a lo-hi-lo doping profile or a Misawa p-i-n doping profile. Alternatively, the diode according to the present invention may be a double drift diode. In a preferred embodiment of the present invention particularly suitable for a single drift diode the narrow bandgap region is located between a heavily doped contact region and the avalanche region so as to maximise the proportion of the avalanche region which can be used to multiply the electrons generated in the narrow bandgap material. In a preferred embodiment of the present invention particularly suitable for a double drift diode the narrow bandgap region may be located within the avalanche region, preferably towards the centre of the avalanche region, so that both the n and p components of the tunnel current may undergo avalanche multiplication.

The IMPATT diode according to the present invention may be made of either III-V semiconductor materials, such as Gallium Arsenide/Aluminium Gallium Arsenide, or group IV semiconductor materials, such as Silicon Germanium/Silicon. The thickness of the narrow bandgap region and the composition of the alloys making up the narrow bandgap region are design parameters chosen to achieve the required tunnel current, as will be apparent to the person skilled in the art.

According to a further preferred embodiment of the present invention the length of the drift region (L_D) and the length of the avalanche region (L_A) are chosen such that the drift region is between 2 and 6 times, and more preferably between 3.5 and 4.5 times, the length of the avalanche region. This ensures that in the fundamental mode of oscillation, the period of oscillation (P) is between 4 and 12 times, and preferably close to 8 times (between 7.5 and 8.5 times), the avalanche region transit time (T_A). It has been found that this substantially reduces the noise generated by an IMPATT diode according to the present invention.

The IMPATT diode according to the present invention can be arranged such that at least part of the tunnel current is generated by optical excitation.

The present invention will now be described with reference to the following Figures in which:

Figure 1 shows the structure of a single drift IMPATT diode according to the present invention.

Figure 2 graphically illustrates the variation in conduction band and valence band edge energies along the IMPATT diode of Figure 1 showing injection by electron tunnelling.

Figure 3 graphically illustrates the variation in conduction band and valence band edge energies along the IMPATT diode of Figure 1 showing injection by optical excitation.

Figure 4 shows the variation of noise with multiplication factor for the device shown in Figure 2 for different periods of the fundamental mode of a generated voltage oscillation.

Figure 5 shows the tunnel current generated in the device of Figure 1 as a function of phase angle where the origin on the horizontal axis of the plot is chosen as 90°, i.e. at the positive peak of the voltage cycle.

Figure 6 shows the current waveform (I) generated in the device of Figure 1 by tunnelling and avalanche as a function of time.

Figure 7a shows the structure of a first embodiment of a double drift IMPATT diode according to the present invention.

Figure 7b graphically illustrates the variation in conduction band and valence band edge energies along the IMPATT diode of Figure 7a.

Figure 8a shows the structure of a second embodiment of a double drift IMPATT diode according to the present invention.

Figure 8b graphically illustrates the variation in conduction band and valence band edge energies along the IMPATT diode of Figure 8a.

Figure 9 shows the structure of a single drift IMPATT diode according to an alternative embodiment of the present invention.

The IMPATT diode (2) shown in Figure 1 is a lo-hi-lo type IMPATT diode, having a heavily doped p^{++} contact region (6), low doped semiconductor regions (8), (10) and (12) and a heavily doped n^{++} contact region (14). However, according to the present invention a narrow band gap region (4) is located between the low doped region (8) and the low doped region (10).

The material compositions, layer thickneses and doping used in the IMPATT diode (2) is selected to generate a desired level of tunnel current at the peak reverse bias voltage applied to the diode (2).

The narrow bangap region (4) makes it easier for electrons to tunnel from the valence band (V) to the conduction band (C) and is effective to inject electrons into the conduction band of the wide bandgap region (10) in a predictable manner. This is shown by the arrow in Figure 2. The electrons injected into the wider bandgap region (10) then undergo avalanche multiplication in the avalanche region (10).

An n-type doping spike (18) separates the low doped region (10) and the low doped region (12) and so forms the boundary between the avalanche region (10) and the drift region (12) of the device (2).

The avalanche region is the region where the impact ionisation is significant and will extend into region (8) although it is unlikely to include all of region (8). As can be seen from Figure 2 the narrow bandgap region (4) is located within the conventional avalanche region and can be considered as part of the avalanche region.

The p^{++} and n^{++} contact regions should have sufficiently high doping levels to form good Ohmic contacts with the metalisation layer of the diode, as is well known in the art. Alternative contact technologies could be used, e.g. the p^{++} region could be replaced by an n^{+} region to form a Shottky barrier with the metalisation layer.

Figure 2 shows the variation in conduction band (C) and valence band (V) edge energies along the IMPATT diode of Figure 1. This is similar to that of a conventional lo-hi-lo diode except for the narrow bandgap region (4) which makes it easier for an electron to tunnel from the valence band to the conduction band at applied reverse bias voltages above the breakdown voltage in order to inject electrons into the region (10). This tunnelling is indicated by the arrow in Figure 2. The gradual reduction in energy of the valence and conduction bands, from left to right in Figure 2, across the intrinsic region (10) means that electrons injected into the intrinsic region (10) undergo avalanche multiplication. It can be seen that the n-type doping spike (18) terminates the avalanche region of the device (2).

The length of the drift region (12) L_D and the length of the avalanche region (L_A) are chosen such that in the fundamental mode of rf oscillation across the electrodes (22) and (24), the period of oscillation (P) of the fundamental mode is between 4 and 12 times, and preferably close to 8 times the avalanche region transit time (T_A), ie. the time it takes for an electron to transit the avalanche region (10). It has been found that this substantially reduces the noise generated by an IMPATT diode. This applies to conventional IMPATT diodes as well as to IMPATT diodes having a narrow bandgap region.

If the fundamental mode of rf voltage oscillation (having a period of oscillation P) begins at t=0, as shown in Figure 6, then an IMPATT diode is generally designed so that the current from the avalanche region

enters the drift region (12) after a time t=P/2 (t=4T in Figure 6), ie. when the fundamental mode of voltage oscillation (V) ends its positive voltage half cycle. In order to achieve maximum negative resistance IMPATT diodes are generally designed so that the transit time through the drift region is close to P/2. Accordingly, the length of the drift region is generally chosen to be $L_D=V_SP/2$, where V_S is the saturated electron drift velocity. The length of the avalanche region will be $L_A=T_A/V_S$,, where T_A is the time it takes for an electron to transit the avalanche region, ie. the avalanche region transit time.

Thus when $P=8T_A$, then because $L_D=V_SP/2$ and $T_A=L_A/V_S$ as discussed above, this leads to the relationship;

$$L_D=4T_AV_S=4L_A,$$

that is, the drift region length L_D is 4 times the avalanche region length L_A. It has been found that this substantially reduces the noise generated by an IMPATT diode according to the present invention.

To demonstrate the principle of the present invention a Silicon Germanium/Silicon based structure according to Figure 1 has been simulated. Where the fraction of Germanium in the Silicon Germanium alloy is denoted by x, the narrow bandgap region (4) was made of a 200A (Angstrom) thick layer of Silicon Germanium with x=0.33. The low doped region (8,10) was made of a 2000A thick layer of intrinsic Silicon. To reduce the strain in the Silicon Germanium layer (4) for stable operation at high power it may be necessary to add Carbon to the Silicon Germanium alloy. For this particular alloy layer thickness and composition it was found that including the Silicon Germanium layer (4) as the first part of an intrinsic avalanche layer (8,10) as indicated in Figure 1 gave a satisfactorily high tunnel current. The magnitude and thickness of the doping spike (18) was chosen to give an average

electric field in the avalanche region (10) of $5x10^5$V/cm. The amplitude of the time variation of the field was taken as 50% of the average field (ie. A=0.5 see below) which gave a peak tunnel current of approximately 1.5amps/cm^2.

Where the narrow band gap region (4) is SiliconGermanium (SiGe) the injection of tunnel current will use the indirect SiGe bandgap. Semiconductor materials, such as, GaAs/AlGaAs or InGaAs/InP or other hetero systems could be used to implement the device (2) shown in Figure 1 such that a tunnel current is injected into the avalanche region at peak reverse bias. Si has the advantage of high thermal conductivity and demonstrated performance at high frequencies up to 300GHz.

The device (2) is reverse biased by applying a constant reverse bias voltage across electrodes (22) and (24) which voltage is close to the reverse bias breakdown voltage of the device. In addition an oscillating voltage variation is generated across the electrodes (22) and (24) by locating the diode (2) in a microwave cavity and appropriately tuning the cavity. As is well known in the art alternative resonant circuits may be used. The inclusion of the narrow band gap region (4) ensures that a relatively high tunnel current is injected into the avalanche region (16) at the peak reverse bias voltage.

Without the narrow bandgap region this injection arises from the reverse saturation current which normally has very low values such that the number of particles available to initiate an avalanche is low, often less than 1, with consequent high statistical fluctuation. The tunnel current is designed to be much higher, yielding much lower noise prior to avalanche.

The tunnel current consists of electrons and holes, and referring to Figure 1, the electrons flow into the avalanche region (10) and the holes

flow into the p^{++} region (8). The electrons flowing into the avalanche region (10) then generate electrons and holes in the Si avalanche region (10) by impact ionisation.

The injected tunnel current is generated entirely in the SiGe narrow bandgap region (4) and comprises a narrow pulse of charge carriers close to the peak reverse bias voltage which pulse of charge carriers is then injected into the Si avalanche region (10). The relatively narrow pulse of injected tunnel current has low statistical fluctuation and will initiate a very low noise avalanche multiplication in the avalanche region (10). The structure of the diode (2) enables a relatively high tunnel current to be injected into the avalanche region (10). Also, because the inclusion of the narrow bandgap region (4) makes it easier for electrons to move from the valence band (V) into the conduction band (C) the diode (2) can be operated at lower electric fields and multiplication values than for a conventional lo-hi-lo type IMPATT diode with similar power outputs. This will yield an improvement in reliability and efficiency.

As indicated above in a preferred embodiment, the narrow bandgap layer (4) is made of a 200A thick layer of 33% Silicon Germanium and the avalanche region (8,10) is made of a 2000A thick layer of Silicon. The fundamental oscillation of the voltage (V) generated across the device (2) will take the form;

$$V = V_0[1+A\cos(\omega t)]$$

with A = a constant multiplier which is less than 1,

V_0 = a reverse bias voltage close to the breakdown voltage, and

$V_0A\cos(\omega t)$ = a sinusoidal voltage,

as is described above. In this case the tunnel current shown in Figure 5 is obtained. In Figure 5 the phase origin of the horizontal axis (ie. phase = 0) is chosen to correspond to the peak reverse bias voltage applied across the electrodes (22) and (24). This peak reverse bias occurs at t=2T on Figure 6, at a 90° phase lag relative to the origin of the rf voltage oscillation at t=0 on Figure 6. The tunnel current is generated entirely in the narrow bandgap region (4) and forms a pulse close to the peak reverse bias voltage which is then injected into the Si avalanche region (10). From Figure 5, it is expected that the tunnel current will approach 1.6 amp/cm^2 in the structure of Figure 2 and should give very low noise avalanche multiplication.

It will be understood by the person skilled in the art that the magnitude of the tunnel current shown in Figure 5 can be varied by changing the thickness or alloy composition of the narrow bandgap layer (4), possibly using multi-quantum wells to alleviate strain. It is also possible to design the doping profile or to use doping spikes to change the electric field across the narrow bandgap region (4) relative to the field across the avalanche region (10).

The origin of phase is defined as the point at which the rf voltage is zero and about to rise (ie. t=0 in Figure 6). The peak tunnel current coincides with the peak electric field which occurs at a phase of 90° (ie. t=2T in Figure 6). The avalanche multiplication is arranged so the total current (ie. tunnel plus avalanche current - I in Figure 6) normally peaks close to a phase of 180° (ie. t=4T in Figure 6) at which the oscillating rf voltage passes through zero to become negative.

As indicated above, the device (2) is reverse biased to just below the breakdown voltage and a periodic voltage is generated across the electrodes (22) and (24). Thus, towards the peak of the positive half cycle of the sinusoidal voltage, the voltage generated across the

electrodes (22) and (24) is greater than the breakdown voltage. The avalanche noise is suppressed most effectively when the period of oscillation of the fundamental mode of voltage oscillation is approximately eight times the avalanche zone transit time, ie. eight times the time it takes a charge carrier to pass through the avalanche zone (10).

In Figure 4 is shown a graph of the computed noise of a device (2) as a function of the multiplication factor of the avalanche region (10) for various periods of oscillation of the sinusoidal voltage applied across the electrodes (22) and (24). The device simulated was a Silicon lo-hi-lo diode having the structure shown in Figure 1 and having a 0.3 micron thick avalanche region (10) with a Silicon Germanium narrow bandgap layer. It can be seen from the Figure 4 graph that the noise at high multiplication levels is reduced when the period of oscillation approaches eight times the avalanche zone transit time, ie. $P=8T_A$ (indicated as P=8 in Figure 4). The excess noise factor at $P=8T_A$ decreases as the multiplication factor increases and can achieve almost noise free multiplication.

In Figure 6 is plotted the total current waveform (I) consisting of tunnel current and avalanche current for the device of Figure 2 when the sinusoidal voltage (V), also shown in Figure 6, has a period of P=8T. The current (I) starts to rise at time t=2T which corresponds to the peak reverse bias voltage (V) of the applied sinusoidal voltage applied across the electrodes (22) and (24) of the device (2). The total current (I) goes through a maximum close to t=4T which corresponds to the time at which the sinusoidal voltage (V) becomes negative.

By using relatively high tunnel currents, efficient power generation should be possible with relatively low multiplication factors, so that the

device (2) can be operated with a lower voltage drop across the avalanche zone. This should improve both efficiency and reliability.

Figure 3 shows the variation in conduction band (C) and valence band (V) edge energies for the device of Figure 1 (assuming Silicon Germanium as the narrow bangap region), except that in this case injection of electrons from the valence band and into the conduction band occurs by optical excitation (represented by arrow α of Figure 3) of the electrons in the narrow bandgap layer as well as by electron tunnelling (represented by arrow β of Figure 3). If electromagnetic radiation with an energy greater than the bandgap of the narrow bandgap material (4) is incident on the narrow bandgap region (4), electrons in the valence band (V) of the narrow bandgap region can absorb a photon (26) of the electromagnetic radiation and jump into the conduction band (C). Excitation in the narrow bandgap region could be done by horizontal access (wave guide) geometries to enhance optical absorption. The narrow bandgap region (4) makes it easier for an electron to jump from the valence band to the conduction band in order to inject electrons into the avalanche region (10). This optical excitation is indicated by the arrow α in Figure 3.

Doping spikes can be used to adjust the electric field across the narrow bandgap layer to achieve the desired ratio of the injection current generated by optical excitation to the injection current generated by tunnelling. There is then a potential for optical injection locking of isolated diodes or arrays of diodes of the type shown in Figure 1 and optical control of the phase and amplitude of the signal output from the diode (2).

Alternatively, as is shown in Figure 9, the narrow bandgap region (4') can be adjacent to but outside of the avalanche region (10'). In this

case a doped region (8') will be required between the narrow bandgap region (4') and the avalanche region (10') in order to change the relative electric fields.

The above description has related to single drift diodes as shown in Figure 1, but the present invention can also be applied to double drift diodes, such as that shown in Figures 7a and 8a. The diodes shown in Figure 7a and 8a are fabricated from a Gallium Arsenide/Aluminium Gallium Arsenide structure

The double drift IMPATT diodes shown in Figures 7a and 8a have heavily doped p^{++} region (42), low doped semiconductor regions (44), (46) and (48) and a heavily doped n^{++} region (50). Region (46) comprises the avalanche region and regions (44) and (48) comprise the two drift regions. A p-type doping spike (54) and an n-type doping spike (56) separate the avalanche region (46) from the drift regions (44) and (48). In the diode shown in Figure 7a a Gallium Arsenide narrow bandgap region (40) is located in the centre of the avalanche region (46). In the diode shown in Figure 8a a Gallium Arsenide narrow bandgap region (52) is located to the left hand side of the avalanche region (46). As described above in relation to the single drift diode of Figure 1, the narrow bandgap regions (40) and (52) make it easier for electrons to tunnel from the valence band (V) to the conduction band (C) in order to reliably inject a tunnel current into the avalanche region.

The material compositions, layer thickness and doping used in the structures of Figure 7a and 8a are selected to generate a desired level of tunnel current at peak reverse bias voltage and appropriate electric field levels in the avalanche region to ensure a desired avalanche multiplication by impact ionisation and in the drift regions to ensure that carriers achieve saturation velocity. As indicated above it is preferred that each drift region (44) and (48) has a length approximately four

times the length of the avalanche region (46). Thus, in the fundamental mode of oscillation the period of the fundamental oscillation will be approximately eight times the transit time of the avalanche region, as discussed above in relation to the diode of Figure 1.

Figures 7b and 8b show the variation in conduction band (C) and valence band (V) edge energies along the IMPATT diodes of Figures 7a and 8a respectively. These are similar to the conduction and valence band edge energies of a conventional double drift diode except for the edge energies at the respective narrow bandgap regions (40) and (52).

CLAIMS

1. An impact ionisation avalanche transit time (IMPATT) diode device comprising an avalanche region and a drift region, wherein a narrow bandgap region, with a bandgap narrower than the bandgap in the avalanche region, is located adjacent to or within the avalanche region in order to generate within the narrow bandgap region a tunnel current which is injected into the avalanche region.

2. An IMPATT diode according to claim 1 wherein the narrow bandgap region is arranged to generate a tunnel current for injection into the avalanche region at the peak reverse bias voltage applied to the diode.

3. An IMPATT diode according to claim 1 or claim 2 wherein the narrow bandgap region is located at the edge of the avalanche region.

4. An IMPATT diode according to any one of the preceding claims wherein the narrow bandgap region is located between a heavily doped contact region and the avalanche region.

5. An IMPATT diode according to any one of the preceding claims wherein the narrow bandgap region comprises one layer of narrow bandgap material.

6. An IMPATT diode according to any one of claims 1 to 4 wherein the narrow bandgap region comprises a plurality of layers of narrow bandgap material.

7. An IMPATT diode according to any one of the preceding claims wherein the diode has a lo-hi-lo doping profile.

8. An IMPATT diode according to claim 7 wherein the diode is a Misawa p-i-n diode.

9. An IMPATT diode according to any one of claims 1 to 6 wherein the diode is a double drift diode.

10. An IMPATT diode according to any one of the preceding claims wherein the diode is made of III-V semiconductor materials.

11. An IMPATT diode according to any one of claims 1 to 7 wherein the diode is made of group IV semiconductor materials.

12. An IMPATT diode according to claim 11 wherein the narrow bandgap region is made of at least one layer of Silicon Germanium and the avalanche region is made of Silicon.

13. An IMPATT diode according to claim 10 wherein the narrow bandgap region is made of at least one layer of Gallium Arsenide and the avalanche region is made of Aluminium Gallium Arsenide.

14. An IMPATT diode according to any one of the preceding claims wherein the length of the drift region or regions is between 2 and 6 times the length of the avalanche region.

15. An IMPATT diode according to claim 14 wherein the length of the drift region or regions is between 3.5 and 4.5 times the length of the avalanche region.

16. An IMPATT diode according to any one of the preceding claimed arranged such that at least part of the tunnel current can be generated by optical excitation.

17. An IMPATT diode substantially as hereinbefore described with reference to the accompanying Figures.

18. A method of operating an IMPATT diode according to any one of the preceding claims such that an oscillating voltage across the diode has a period of between 4 and 12 times the transit time of the avalanche region.

19. A method according to claim 18 wherein the oscillating voltage has a period of between 7.5 and 8.5 times the transit time of the avalanche region.

20. A method of operating an IMPATT diode according to any one of claims 1 to 17 including the step of optically exiting at least part of the tunnel current.

21. A method of operating an IMPATT diode substantially as hereinbefore described with reference to the accompanying Figures.

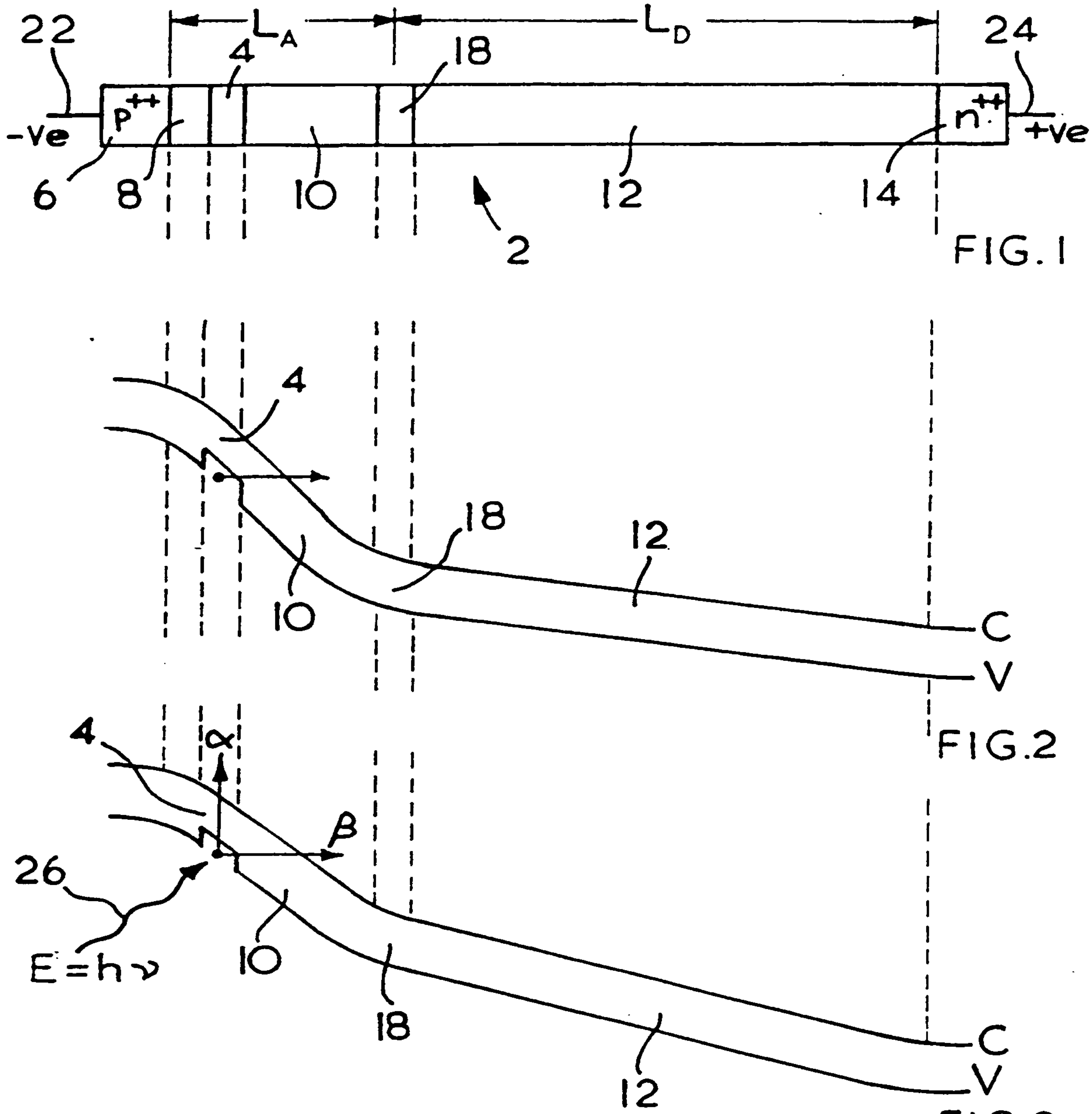


FIG. 1

FIG. 2

FIG. 3

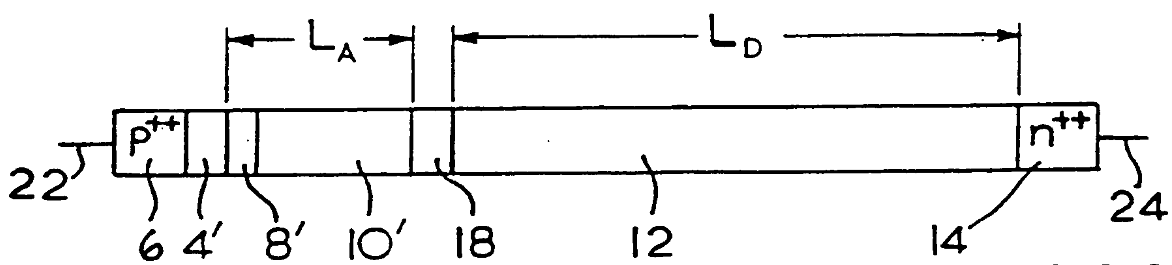


FIG. 9

FIG. 4

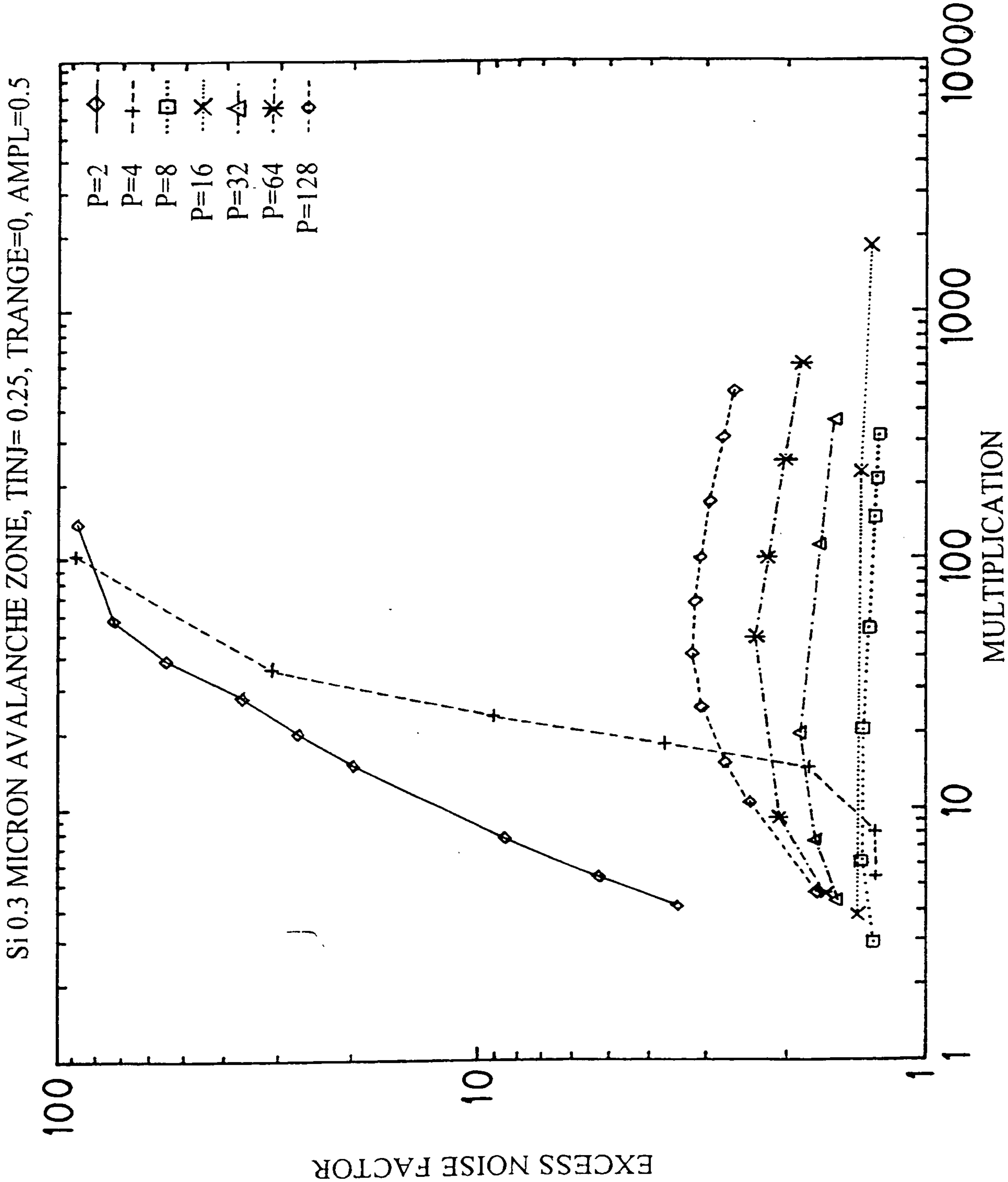
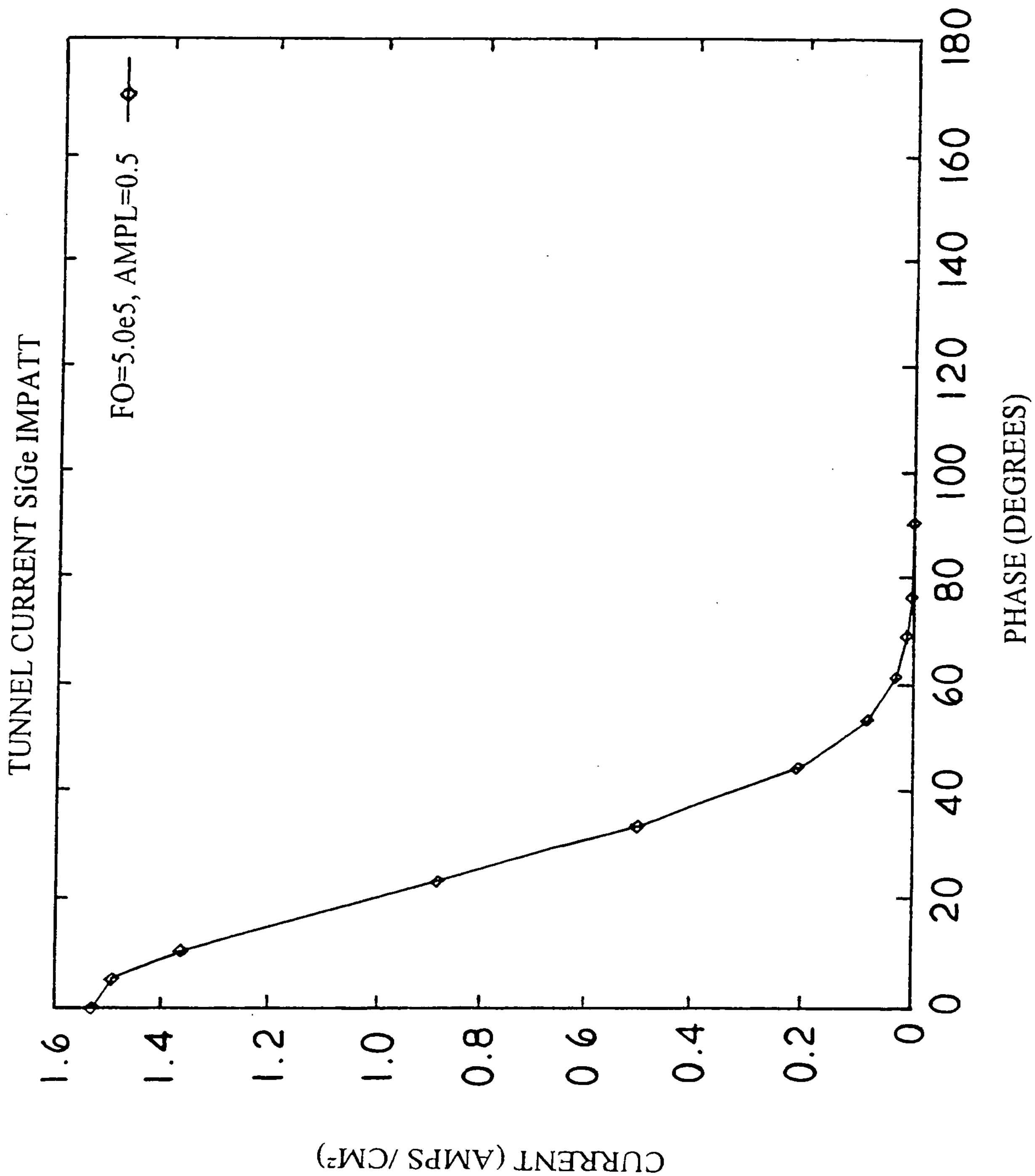

Si 0.3 MICRON AVALANCHE ZONE, TINJ= 0.25, TRANGE=0, AMPL=0.5
P=2
P=4
P=8
P=16
P=32
P=64
P=128
EXCESS NOISE FACTOR
100
10
1
MULTIPLICATION
1
10
100
1000
10000

FIG. 5


TUNNEL CURRENT SiGe IMPATT
FO=5.0e5, AMPL=0.5
PHASE (DEGREES)
0 20 40 60 80 100 120 140 160 180
CURRENT (AMPS /CM²)
0 0.2 0.4 0.6 0.8 1.0 1.2 1.4 1.6

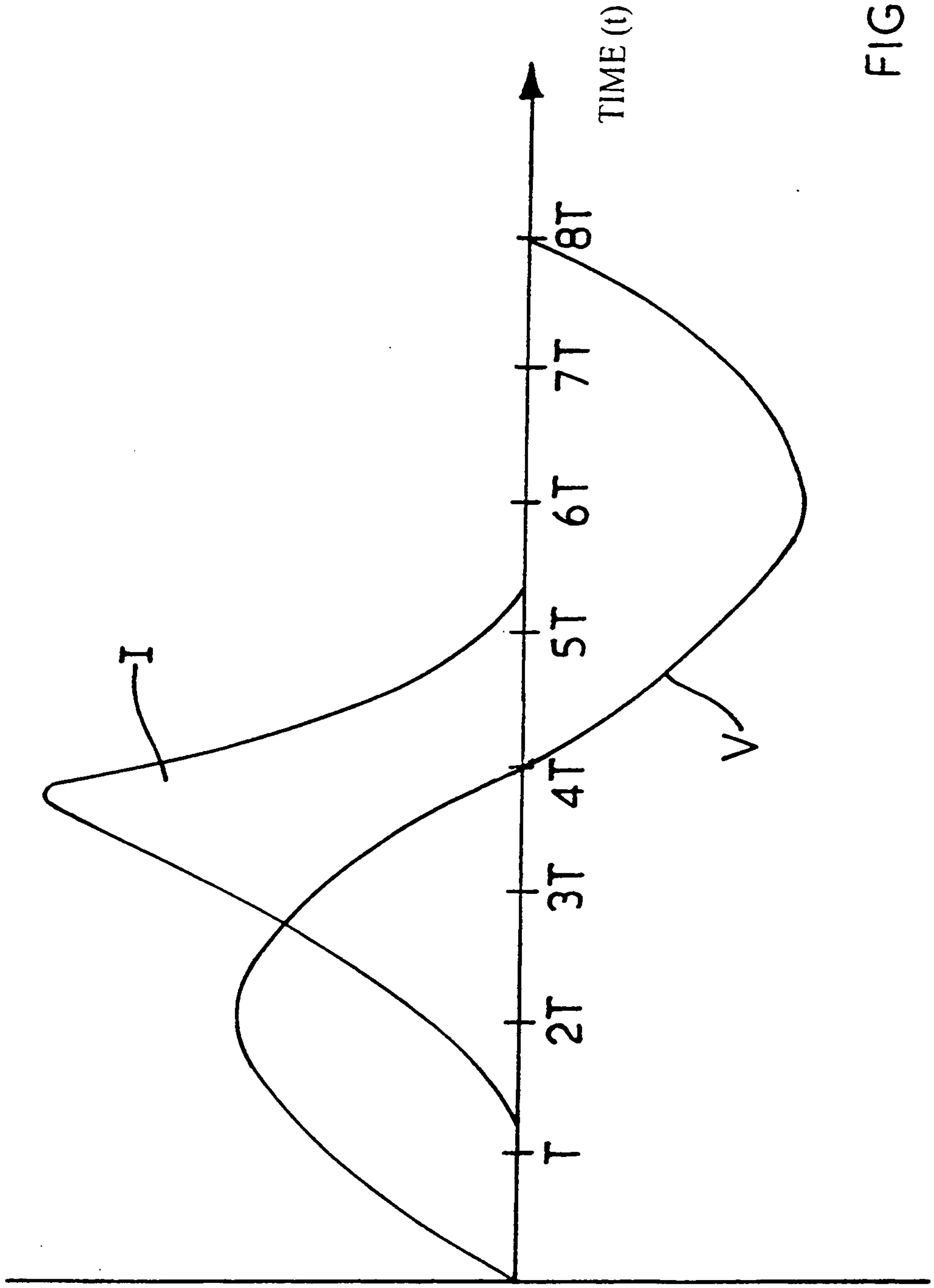


FIG. 6

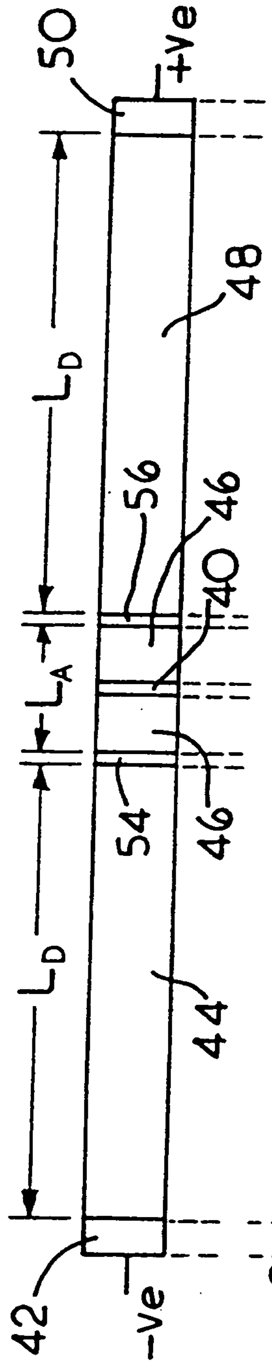


FIG. 7a

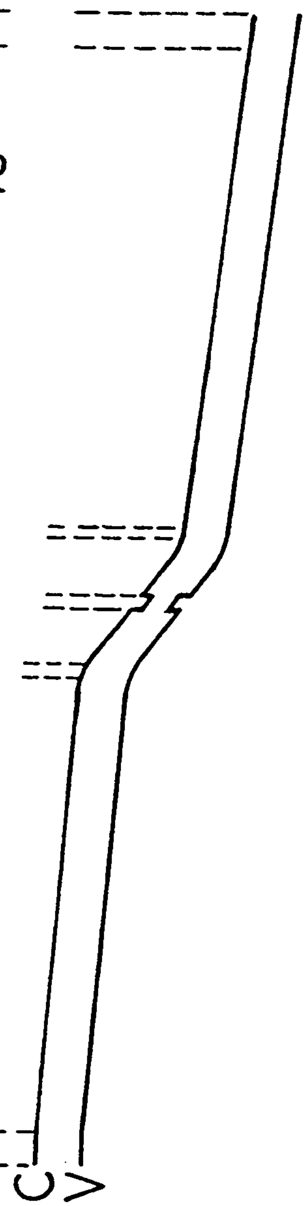


FIG. 7b

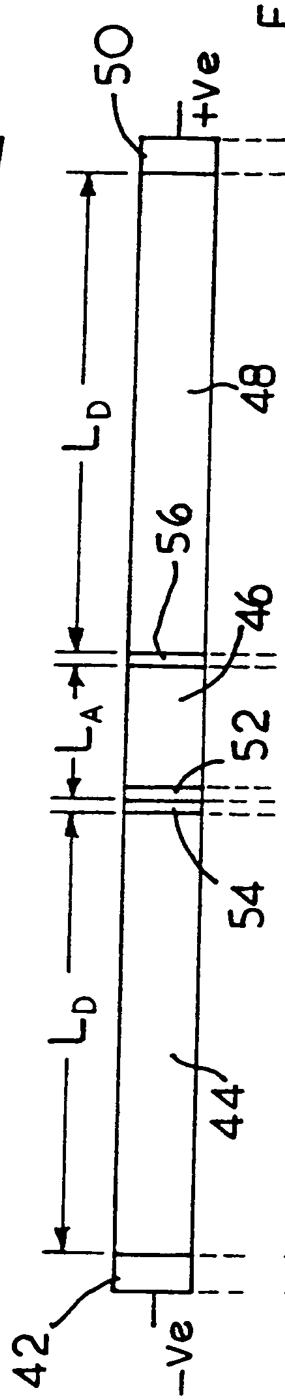


FIG. 8a

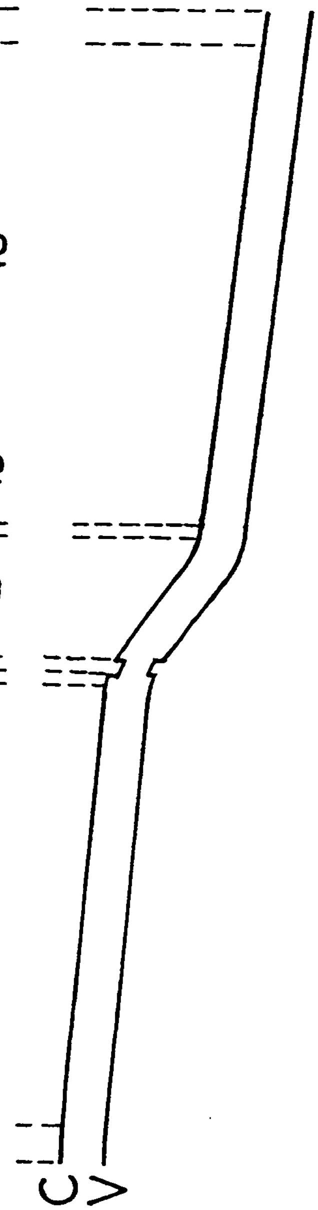


FIG. 8b

INTERNATIONAL SEARCH REPORT

International Application No
PCT/GB 99/03428

A. CLASSIFICATION OF SUBJECT MATTER
IPC 7 H01L29/864

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 7 H01L

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	EP 0 262 346 A (LICENTIA GMBH) 6 April 1988 (1988-04-06)	1-6,8, 11,12, 16,17,21
A	page 3, column 4, line 22 - line 23; figures 1,2	14,15, 18,19
X	MISHRA J K ET AL: "DESIGN OPTIMIZATION OF A SINGLE-SIDED SI/SIGE HETEROSTRUCTURE MIXEDTUNNELLING AVALANCHE TRANSIT TIME DOUBLE DRIFT REGION" SEMICONDUCTOR SCIENCE AND TECHNOLOGY,GB,INSTITUTE OF PHYSICS. LONDON, vol. 12, no. 12, page 1635-1640 XP000724838 ISSN: 0268-1242 page 1636, column 2, paragraph 3	1-6,9, 11,12, 16,17,21

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[X] Further documents are listed in the continuation of box C.

[X] Patent family members are listed in annex.

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"O" document referring to an oral disclosure, use, exhibition or other means

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"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
13 January 2000	24/01/2000

Name and mailing address of the ISA	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax: (+31-70) 340-3016	Juhl, A

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International Application No
PCT/GB 99/03428

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication,where appropriate, of the relevant passages	Relevant to claim No.
X	GB 2 002 579 A (THOMSON CSF) 21 February 1979 (1979-02-21) figure 2 ---	1-6,10, 17,21
X	US 5 466 965 A (MENG CHARLES C ET AL) 14 November 1995 (1995-11-14)	1-7,10, 13,16, 17,20,21
A	figure 1 ---	14,15
X	EP 0 757 392 A (HITACHI EUROP LTD) 5 February 1997 (1997-02-05) page 6, line 19; figures 35,36 page 19, line 2 ---	1-5,7,8, 10
X	MISHRA J K ET AL: "AN EXTREMELY LOW NOISE HETEROJUNCTION IMPATT" IEEE TRANSACTIONS ON ELECTRON DEVICES,US,IEEE INC. NEW YORK, vol. 44, no. 12, page 2143-2148 XP000724127 ISSN: 0018-9383 figure 1 ---	1,2,10
X	KEARNEY M J: "HETEROJUNCTION IMPACT AVALANCHE TRANSITTIME DIODES GROWN BY MOLECULAR BEAM EPITAXY" SEMICONDUCTOR SCIENCE AND TECHNOLOGY,GB,INSTITUTE OF PHYSICS. LONDON, vol. 8, no. 4, page 560-567 XP000368239 ISSN: 0268-1242 figure 1 -----	1,7,13

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INTERNATIONAL SEARCH REPORT

Information on patent family members

International Application No
PCT/GB 99/03428

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